ELSEVIER
SCIENCE DIRECT®
PHYSICS LETTERS B
Physics Letters B 550 (2002) 16–23
www.elsevier.com/locate/npe

Prediction of charm-production fractions in neutrino interactions

G. De Lellis, F. Di Capua, P. Migliozzi

Università "Federico II" and INFN, Napoli, Italy

Received 16 October 2002; accepted 30 October 2002
Editor: L. Montanet

Abstract

The way a charm-quark fragments into a charmed hadron is a challenging problem both for the theoretical and the experimental particle physics. Moreover, in neutrino induced charm-production, peculiar processes occur such as quasi-elastic and diffractive charm-production which make the results from other experiments not directly comparable. We present here a method to extract the charmed fractions in neutrino induced events by using results from e^+e^-, πN, γN experiments while taking into account the peculiarities of charm-production in neutrino interactions. As results, we predict the fragmentation functions as a function of the neutrino energy and the semi-muonic branching ratio, B_μ, and compare them with the available data.

1. Introduction

The problem of how a charm-quark fragments into a charmed hadron is challenging both from the theoretical and the experimental point of view. Indeed, perturbative QCD is not applicable at energies comparable with the charm-quark mass. Therefore, parameterizations have to be used and the parameters are determined experimentally. In the experiments the direct identification of the charmed hadron in the final state is only possible through the visual observation of the hadron decay and the measurement of the kinematical variables, practically feasible only with nuclear emulsions.

In the following, we focus on the so-called charm-production fractions (f_h's); i.e., the probability that a charm-quark fragments into a charmed hadron h ($= D^0, D^+, D_s, \Lambda_c$).

In this Letter we review all existing data on charm-production fractions as measured by e^+e^-, πN and γN experiments and predict f_h in neutrino induced charm-production. Indeed, data on charmed fractions in interactions induced by neutrinos are rather scarce. Only one experiment, E531 [1], measured f_h with a statistics of 122 events with an identified charmed hadron in the final state.

After a thorough overview of all available data, we present a method to extract f_h for neutrino experiments. The major difference of this method with respect to other presented in the past, i.e., see Ref. [2], is that f_h's from e^+e^- are not extrapolated to neutrino experiments straightway, but some peculiarities of ν-induced interactions are accounted for. Indeed, neutrinos may undergo to quasi-elastic and diffractive processes with production of charmed hadrons in the final state. These results are also used to estimate the

E-mail address: pasquale.migliozzi@cern.ch (P. Migliozzi).

0370-2693/02
PII: S0370-2693(02)02954-4

Table 1
Measured cross-sections for the production of charmed hadrons at center of mass energies ($\sqrt{s}$) in the range 4.03–10.55 GeV

$\sqrt{s}$ (GeV)	$\sigma(D^0)$ (nb)	$\sigma(D^+)$ (nb)	$\sigma(D^{\star 0})$ (nb)	$\sigma(D^{\star +})$ (nb)	$\sigma(D_s^+)$ (nb)	$\sigma(\Lambda_c^+)$ (nb)
4.03 [5]	19.9 ± 2.4	6.5 ± 0.8	–	–	–	–
4.14 [5]	9.3 ± 2.4	1.9 ± 0.9	–	–	–	–
4.16 [6]	7.8 ± 0.8	2.1 ± 0.7	–	–	–	–
5.20 [6]	4.7 ± 0.8	1.7 ± 0.4	–	–	–	–
10.55 [7]	1.36 ± 0.16	0.57 ± 0.08	0.78 ± 0.17	0.65 ± 0.05	0.41 ± 0.13	0.20 ± 0.08
10.55 [8]	1.14 ± 0.15	0.56 ± 0.08	–	0.54 ± 0.08	0.42 ± 0.07	0.45 ± 0.07

semi-muonic branching ration of charmed hadrons. Finally, we discuss the statistical and systematic uncertainties associated with our predictions and compare them with the E531 results.

2. Charm-production fraction in DIS interactions

2.1. Measurement of the D^+/D^0 ratio

In this section we give an overview of the available data on D^+/D^0 measurements in e^+e^-, πN, pN and γN experiments. Furthermore, we also study the correlated variable F_V, which is defined as $V/(V+P)$, where V and P signify vector and pseudo-scalar charmed mesons, respectively. When needed, we recomputed F_V by using the latest charmed-hadron branching-ratios (BR). Finally, we extract for the first time F_V from neutrino induced charm-production data.

In the following we assume that $D^{\star 0}$ and $D^{\star +}$ production cross-sections are equal at the parton level, as well as the direct production of D^0 and D^+.

From here on, we indicate with D the sum of both prompt and decayed ($D^\star \to D$) D meson production.

Under the previous assumptions, the measurement of D^+/D^0 and $D^\star/D$ ratios allows us to extract F_V. By using the formulae given in Ref. [3], F_V can be extracted from the relations

$$F_V \times B_\star = \frac{1-R_1}{1+R_1}, \qquad (1)$$

$$F_V \times B_\star = \frac{R_2}{1-R_2}, \qquad (2)$$

where $R_1 \equiv D^+/D^0$, $R_2 \equiv (D^0 \text{ from } D^{\star +})/D^0$ and $B_\star = \mathrm{BR}(D^{\star +} \to D^0\pi^+) = (67.7 \pm 0.5)\%$ [4].

2.1.1. e^+e^- experiments

The basic principle to reconstruct e^+e^- events with charmed hadrons in the final state is common to all the experiments. Being a $c\bar{c}$ pair produced in the annihilation, one charmed hadron is used to tag the events, while the other one to study the decay properties. The decay modes used to tag the event are[1]

$$D^{\star +} \to D^0\pi^+ \to (K^-\pi^+)\pi^+ (0.026 \pm 0.006),$$
$$D^0 \to K^-\pi^+ (0.0383 \pm 0.0009),$$
$$D^0 \to K^-\pi^+\pi^+\pi^- (0.0749 \pm 0.0031),$$
$$D^+ \to K^-\pi^+\pi^+ (0.090 \pm 0.006),$$

where the corresponding branching ratios are also given in brackets [4].

Results on the total cross-sections for inclusive production of the charmed particles $D^{\star 0}$, $D^{\star +}$, D^0 and D^+ at various $\sqrt{s}$ are shown in Table 1.

A complete review of the probabilities ($f(c \to C)$) that a c-quark fragments into a $D^\star$, D^0, D^+ and other charmed hadrons as measured in Z^0 decays is given in Ref. [9] and reported in Table 2.

From Tables 1 and 2 we can extract both R_1 and F_V, the latter being estimated by using Eqs. (1) and (2). The results are given in Table 3 and show that within the experimental errors, both R_1 and F_V are independent of the energy.

2.1.2. πN and γN experiments

Several experiments have studied charm-production and extracted R_1 and F_V by using π beams of different energies impinging onto different targets. A non-exhaustive list of all available data in πN experiments is given in Table 4.

[1] Here and in the following by D^+ ($D^{\star +}$) we implicitly indicate also the charge conjugated decay modes.

Table 2
Measured and averaged probabilities that a charm-quark fragments into D^0, D^+, D_s, Λ_c and $D^{\star +}$ in e^+e^- annihilation at $\sqrt{s} = M_{Z^0}$

	ALEPH	DELPHI	OPAL	Weighted average
$f(c \to D^0)$ (%)	$55.9 \pm 1.7 \pm 1.5$	$54.5 \pm 1.5 \pm 3.2$	$58.8 \pm 4.1 \pm 4.0$	55.8 ± 1.8
$f(c \to D^+)$ (%)	$23.8 \pm 0.8 \pm 1.3$	$22.6 \pm 0.8 \pm 1.4$	$23.1 \pm 3.0 \pm 2.0$	23.2 ± 1.0
$f(c \to D_s)$ (%)	$11.5 \pm 1.9 \pm 0.7$	$12.4 \pm 1.1 \pm 1.2$	$9.0 \pm 2.4 \pm 1.1$	11.5 ± 1.1
$f(c \to \Lambda_c)$ (%)	$7.8 \pm 0.8 \pm 0.4$	$8.6 \pm 1.8 \pm 1.0$	$4.8 \pm 2.2 \pm 0.8$	7.6 ± 0.8
$f(c \to D^{\star +})$ (%)	$23.3 \pm 1.0 \pm 0.8$	$25.5 \pm 1.5 \pm 0.6$	22.8 ± 0.9	23.4 ± 0.7

Table 3
Measured R_1, R_2, F_V in e^+e^- experiments as a function of $\sqrt{s}$ and their averaged values

$\sqrt{s}$ (GeV)	R_1	R_2	$F_V(R_1)$	$F_V(R_2)$
4.03 [5]	0.33 ± 0.06	–	0.74 ± 0.10	–
4.14 [5]	0.20 ± 0.11	–	0.91 ± 0.23	–
4.16 [6]	0.27 ± 0.09	–	0.85 ± 0.16	–
5.20 [6]	0.36 ± 0.10	–	0.70 ± 0.16	–
10.55 [7,8]	0.45 ± 0.06	0.32 ± 0.04	0.56 ± 0.08	0.70 ± 0.13
M_{Z^0}	0.42 ± 0.03	0.28 ± 0.01	0.60 ± 0.04	0.57 ± 0.03
Weighted average	0.39 ± 0.02	0.29 ± 0.01	0.65 ± 0.03	0.60 ± 0.03

Table 4
Summary of available R_1, R_2 and F_V measurements extracted from πN experiments. For details see Refs. [10,11]

	R_1	R_2	$F_V(R_1)$	$F_V(R_2)$
WA92: 350 GeV/c π^- on Cu, W	0.423 ± 0.012	0.280 ± 0.015	0.60 ± 0.02	0.57 ± 0.04
E769: 250 GeV/c π^- on Be, Al, Cu, W	0.419 ± 0.043	0.222 ± 0.031	0.60 ± 0.06	0.42 ± 0.08
E769: 210 GeV/c π^- on Be, Al, Cu, W	0.258 ± 0.058	–	0.87 ± 0.11	–
E653: 600 GeV/c π^- on emulsion	0.393 ± 0.032	–	0.64 ± 0.05	–
NA32: 230 GeV/c π^- on Cu	0.422 ± 0.033	0.262 ± 0.026	0.60 ± 0.05	0.52 ± 0.07
NA32: 200 GeV/c π^- on Si	$0.439^{+0.123}_{-0.094}$	0.319 ± 0.095	0.58 ± 0.16	0.69 ± 0.30
NA27: 360 GeV/c π^- on H	0.564 ± 0.171	–	0.41 ± 0.21	–
Weighted average	0.415 ± 0.010	0.268 ± 0.012	0.611 ± 0.015	0.541 ± 0.033

The NA14/2 photo-production experiment [3] measured both $R_1 = 0.37 \pm 0.10$ and $R_2 = 0.26 \pm 0.04$ from which we can extract the weighted average $F_V = 0.57 \pm 0.09$.

From these data we can conclude that, within the experimental errors, R_1 is both process- and energy-independent.

2.1.3. νN experiments

Recently two measurements which allowed us to extract for the first time F_V from neutrino experiments became available. In Ref. [12] the CHORUS Collaboration presented a measurement of the production rate of D^0 based on a sample of about 26 000 ν_μ charged-current events interactions located and analyzed so far in the target emulsions. After reconstruction of the event topology in the vertex region, 283 D^0 decays were observed with an estimated background of 9.2 events from K^0 and Λ decays. The CHORUS Collaboration measured the D^0 production cross-section times $\mathrm{BR}(D^0 \to V2) + \mathrm{BR}(D^0 \to V4)]$ [13]. The total cross-section has been extracted by accounting for the D^0 decays into all neutrals. The value we used is $\mathrm{BR}(D^0 \to \text{ all neutral}) = (25 \pm 5)\%$ [14].

Therefore, the D^0 production cross-section normalized to ν_μ charged-current (CC) interactions is

$$\frac{\sigma(D^0)}{\sigma_{\mathrm{CC}}} = (2.65 \pm 0.18 \pm 0.24 \pm 0.50) \times 10^{-2} \tag{3}$$

at 27 GeV average ν_μ energy. Notice that this measurement includes both D^0 prompt and D^0 from the decay of $D^\star$ mesons.

Table 5
Summary of the available data on F_V and predictions from different models. The error for the theoretical predictions is not shown being relevant only for the third digit

		F_V (meas)	F_V (UCLA)	F_V (JETSET)	F_V (HERWIG)
e^+e^-	$\sqrt{s} = 4.03$ GeV	0.74 ± 0.10	0.47	0.52	0.54
e^+e^-	$\sqrt{s} = 4.14$ GeV	0.91 ± 0.23	0.62	0.70	0.66
e^+e^-	$\sqrt{s} = 4.16$ GeV	0.85 ± 0.16	0.63	0.71	0.66
e^+e^-	$\sqrt{s} = 5.20$ GeV	0.70 ± 0.16	0.59	0.70	0.28
e^+e^-	$\sqrt{s} = 10.55$ GeV	0.56 ± 0.08	0.61	0.74	0.38
e^+e^-	$\sqrt{s} = 91.2$ GeV	0.60 ± 0.04	0.61	0.75	0.39
πN	$E_\pi = 200$–350 GeV	0.61 ± 0.02	–	–	–
γN		0.57 ± 0.09	–	–	–
νN	$E_\nu \sim 25$ GeV	0.50 ± 0.12	–	0.69	0.27

The $D^{\star+}$ production in ν_μ charged-current interactions has been measured, with a similar ν_μ beam, by the BEBC [15] and NOMAD [16] experiments to be $(1.22 \pm 0.25) \times 10^{-2}$ and $(0.79 \pm 0.20) \times 10^{-2}$, respectively. The weighted average $D^{\star+}$ production rate normalized to ν_μ charged-current interactions is

$$\frac{\sigma(D^{\star+})}{\sigma_{\mathrm{CC}}} = (0.96 \pm 0.16) \times 10^{-2}. \tag{4}$$

From the measured ratios (3) and (4), and by knowing $B_\star$, we can compute $R_2 = 0.25 \pm 0.06$. From the latter value and from Eq. (2) we can extract

$$F_V = 0.50 \pm 0.12.$$

It is worth to notice that R_1 and F_V extracted from neutrino experiments can be compared straightway to e^+e^-, πN and γN results, being D^+ and D^0 either produced promptly or from the decay of prompt $D^{\star+}$ and $D^{\star0}$. Namely, processes peculiar of ν interactions do not affect R_1 and F_V.[2]

2.1.4. *Summary and discussion of all available data on R_1 and F_V*

From results reported in the previous sections, we can argue that within the experimental errors R_1 is constant over a wide range of energies ($\sqrt{s} \sim 4$–90 GeV) and independent of the process. The constant behavior of R_1 down to $\sqrt{s} \sim 4$ GeV can be derived with simple arguments:

- the masses of $D^+(1869.3)$, $D^0(1864.5)$, $D^{\star+}(2010.0)$ and $D^{\star0}(2006.7)$ are very similar. Therefore, the threshold suppression of $D^\star$ mesons which tends to enhance D^+ contribution, is very little;
- whatever $D^\star/D$ meson is produced a pion should be always created. Therefore, all charmed mesons have the same threshold behavior, which cancels out in the ratio.

For these reasons we assume that R_1 measured in e^+e^- (see Table 3) can be used in neutrino induced charm-production, too.

As an important by product of our study we have also extracted F_V from different processes and at several energies (see Table 5). The simplest model to predict F_V is based on the spin-counting. Namely, vector mesons are spin-one states ($^3\mathrm{S}_1$), while pseudoscalar mesons are spin-zero states ($^1\mathrm{S}_0$), therefore $F_V = 0.75$. The discussion of more refined models (UCLA, JETSET, HERWIG and others) is beyond the purposes of this Letter. For details we refer to [17].

From Table 5 we can see that the measured F_V is independent of the processes and of the energy. This means that the probability for a c-quark to fragment into a D or a $D^\star$ meson is universal and does not depend neither on the process nor on the energy. Notice that the UCLA model is the best in describing available e^+e^- data.

2.2. *Measurement of the D_s to D^0 and Λ_c to D^0 ratios*

The ratio D_s/D^0 has been measured in e^+e^-, πN and γN experiments. A summary of the available data is given in Table 6.

[2] In neutrino interactions $D^{(\star)+}$ may also be produced diffractively but, due to the V_{cd} suppression, its rate is expected to be about $(1.6 \pm 0.3) \times 10^{-4}$ with respect to CC interactions and therefore negligible.

Table 6
Summary of the available R_s and R_c measurements extracted from e^+e^-, νN and γN experiments. The πN data have been taken from Refs. [10,11] and references therein, while γN results from Ref. [3]

$\sqrt{s}$ (GeV)	$R_s \equiv D_s/D^0$	$R_c \equiv \Lambda_c/D^0$
4.14 [5]	0.176 ± 0.076	–
10.55 [7]	0.148 ± 0.052	0.148 ± 0.052
10.55 [8]	0.184 ± 0.040	0.158 ± 0.039
M_{Z^0} (ALEPH)	0.206 ± 0.039	0.140 ± 0.017
M_{Z^0} (DELPHI)	0.228 ± 0.033	0.158 ± 0.039
M_{Z^0} (OPAL)	0.153 ± 0.047	0.082 ± 0.041
WA92: 350 GeV/c π^- on Cu	0.160 ± 0.037	–
WA92: 350 GeV/c π^- on W	0.183 ± 0.068	–
NA14/2 (γN)	0.185 ± 0.083	–
Weighted average	0.193 ± 0.016	0.135 ± 0.015

The decay mode used to tag the event is

$$D_s^+ \to \phi\pi^+ \to (K^-K^+)\pi^+$$

whose BR, as reported by the Particle Data Group, are [4]:

$$\mathrm{BR}\big(D_s^+ \to \phi\pi^+\big) = 0.036 \pm 0.009,$$
$$\mathrm{BR}\big(\phi \to K^-K^+\big) = 0.492 \pm 0.007.$$

From Table 6 we can see that the D_s/D^0 ratio is, within the errors, independent of the energy and of the process.

Data on the ratio Λ_c/D^0 are very poor. Indeed, it has been measured only in e^+e^- experiments (see Table 6).

The decay mode used to tag the event is

$$\Lambda_c \to pK^-\pi^+$$

whose BR, as reported by the Particle Data Group, is [4]:

$$\mathrm{BR}\big(\Lambda_c \to pK^-\pi^+\big) = 0.050 \pm 0.013.$$

From Table 6 we can see that, although with a smaller statistical accuracy, both R_s and R_c are, within the errors, independent of the energy.

2.2.1. Summary and discussion of all available data on R_s and R_c

Although from Table 6 it seems that R_s is constant over a wide range of energies ($\sqrt{s} \sim$ 4–90 GeV) and independent of the process, some comments are in order.

Given the quark composition of the $D_s^+(c\bar{s})$ meson, it has to be created always together with at least one K meson. Therefore, being $m_K \approx 500$ MeV, we expect that the threshold effect for D_s production is more pronounced than for D mesons, when at least one π has to be produced ($m_\pi \approx 100$ MeV). To account for the different threshold effect at low energies, in the following we do not use the R_s values measured at the Z^0 peak. Furthermore, under the assumption that $\sqrt{s}$ in collider experiments can be replaced with W in fixed target experiments, W being the final state hadronic mass, and noting that neutrino-induced charm events at present experiments are characterized by values of W in the range 4–10 GeV, we can argue a R_s value of $R_s = 0.171 \pm 0.029$ which corresponds to the weighted average of the first three results in Table 6.

The available measurements on R_c are very poor. Nevertheless, as it will be discussed in Section 3, we do not use the R_c value to predict the charmed fractions in events induced by neutrinos.

3. Charm-production fractions in neutrino experiments

3.1. The method

From the previous sections we can argue that once a charm-quark has been produced in deep-inelastic interactions (i.e., the energy of the process is higher than the threshold), it has a probability to produce a charmed hadron C_h which is, within the experimental errors, independent of the process and of the energy. Therefore, as far as the deep-inelastic scattering (DIS) is concerned, we can write the charm production rate as

$$\frac{\sigma_c(\mathrm{DIS})}{\sigma_{\mathrm{CC}}} = \frac{\sigma_{D^0}}{\sigma_{\mathrm{CC}}} + \frac{\sigma_{D^+}}{\sigma_{\mathrm{CC}}} + \frac{\sigma_{D_s}}{\sigma_{\mathrm{CC}}} + \frac{\sigma_{\Lambda_c}}{\sigma_{\mathrm{CC}}}$$
$$= \frac{\sigma_{D^0}}{\sigma_{\mathrm{CC}}}(1 + R_1 + R_s + R_c). \qquad (5)$$

In the case of neutrino induced charm-production, Eq. (5) is not correct. Indeed, in this case we also have to account for diffractive and quasi-elastic charm-production. Therefore, the inclusive charm-production

Table 7
Prediction of charm-production fractions in neutrino induced events as a function of the neutrino energy

E_ν (GeV)	f_{D^0}	f_{D^+}	$f_{D_s^+}$	$f_{\Lambda_c^+}$
5	0.32 ± 0.05	0.12 ± 0.02	0.054 ± 0.015	0.50 ± 0.18
10	0.46 ± 0.07	0.18 ± 0.03	0.078 ± 0.022	0.29 ± 0.11
15	0.50 ± 0.08	0.20 ± 0.03	0.13 ± 0.04	0.18 ± 0.07
20	0.52 ± 0.09	0.20 ± 0.04	0.13 ± 0.04	0.14 ± 0.05
25	0.53 ± 0.10	0.21 ± 0.04	0.14 ± 0.04	0.12 ± 0.05
30	0.54 ± 0.10	0.21 ± 0.04	0.14 ± 0.04	0.11 ± 0.05
35	0.54 ± 0.10	0.21 ± 0.04	0.14 ± 0.04	0.11 ± 0.04
40	0.54 ± 0.11	0.21 ± 0.04	0.14 ± 0.04	0.11 ± 0.04
50	0.55 ± 0.12	0.21 ± 0.05	0.14 ± 0.04	0.10 ± 0.04
60	0.55 ± 0.12	0.22 ± 0.05	0.14 ± 0.04	0.09 ± 0.04
70	0.56 ± 0.13	0.22 ± 0.05	0.14 ± 0.04	0.08 ± 0.04
80	0.57 ± 0.14	0.22 ± 0.06	0.14 ± 0.04	0.06 ± 0.03
90	0.58 ± 0.15	0.23 ± 0.06	0.15 ± 0.04	0.04 ± 0.02
100	0.60 ± 0.16	0.23 ± 0.06	0.15 ± 0.05	0.02 ± 0.01
CHORUS	0.524 ± 0.036	0.204 ± 0.014	0.128 ± 0.012	0.147 ± 0.008

rate in neutrino interactions can be written as

$$\frac{\sigma_c(\nu)}{\sigma_{CC}} = \frac{\sigma_c(\text{DIS})}{\sigma_{CC}} + \frac{\sigma_{D_s}}{\sigma_{CC}}\bigg|_{\text{diff}} + \frac{\sigma_{\Lambda_c}}{\sigma_{CC}}\bigg|_{\text{QE}}. \tag{6}$$

If one accepts that R_1, R_s and R_c from e^+e^- (with $\sqrt{s} = 4.1$–90 GeV) and other experiments can be used to described the fragmentation of charm-quarks produced in DIS neutrino interactions with average final state hadronic mass $\langle W \rangle \sim 10$ GeV, then

$$\frac{\sigma_c(\nu)}{\sigma_{CC}} = \frac{\sigma_{D^0}}{\sigma_{CC}}(1 + R_1 + R_s + R_c) + \frac{\sigma_{D_s}}{\sigma_{CC}}\bigg|_{\text{diff}} + \frac{\sigma_c}{\sigma_{CC}}\bigg|_{\text{QE}}. \tag{7}$$

From Eq. (7) charm-production fractions in neutrino interactions can be written as

$$f_{D^0}(E_\nu) = \frac{\sigma_{D^0}}{\sigma_{CC}}(E_\nu)\frac{1}{\frac{\sigma_c(\nu)}{\sigma_{CC}}(E_\nu)},$$

$$f_{D^+}(E_\nu) = R_1\frac{\sigma_{D^0}}{\sigma_{CC}}(E_\nu)\frac{1}{\frac{\sigma_c(\nu)}{\sigma_{CC}}(E_\nu)},$$

$$f_{D_s^+}(E_\nu) = \left(R_s\frac{\sigma_{D^0}}{\sigma_{CC}}(E_\nu) + \frac{\sigma_{D_s}}{\sigma_{CC}}\bigg|_{\text{diff}}(E_\nu)\right)\frac{1}{\frac{\sigma_c(\nu)}{\sigma_{CC}}(E_\nu)}.$$

Notice that, given the poor knowledge on R_c and on the quasi-elastic charm-production cross-section, we derive f_{Λ_c} by using the normalization constrain $f_{D^0} + f_{D^+} + f_{D_s^+} + f_{\Lambda_c^+} = 1$. In order to estimate the charmed fractions and their energy dependence, we use the following inputs:

- the inclusive charm-production rate derived in Ref. [18];
- the energy dependence of the D^0 production rate reported in Ref. [12] properly scaled to account for the effect discussed in Section 2.1.3;
- the energy dependence of the diffractive D_s production given in [19], properly scaled in order to reproduce the average diffractive charm-production cross-section as measured by BEBC and NuTeV [20] ($\frac{\sigma_{D_s}}{\sigma_{CC}}|_{\text{diff}} = (0.31 \pm 0.05) \times 10^{-2}$).

3.2. Results on f_h and B_μ and comparison with the data

By using the method described in the previous section, we derived the charm-production fractions, as a function of the neutrino energy, as reported in Table 7 and shown in Fig. 1. Our results are in good agreement with the charm-production fractions extracted from the E531 data, see Fig. 1. It is worth noticing that $f_{\Lambda_c^+}$ shows a dependence on the energy, higher values at low neutrino energies, consistent with the expectations. Indeed, quasi-elastic charm-production, which yields only Λ_c, is expected to largely contribute to $\sigma_c(\nu)$ for $E_\nu < 25$ GeV [2]. In Table 7 the expected charm-production fractions in the CHORUS experiment are also given.

Having determined the f_h's, we can also estimate the semi-muonic branching ratio B_μ of the charmed hadrons as a function of the neutrino energy. B_μ is

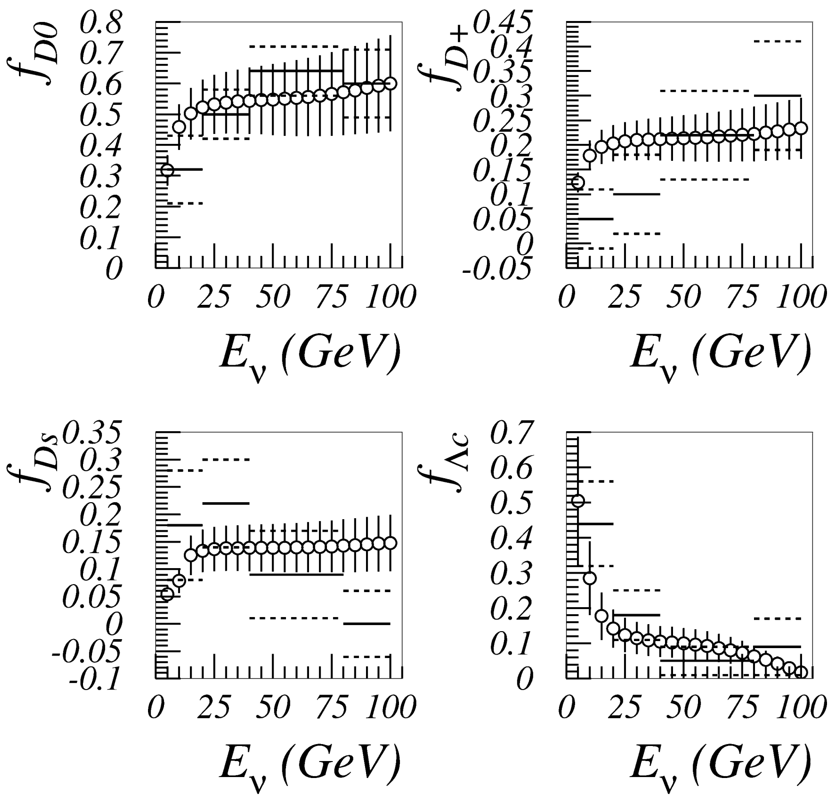

Fig. 1. Predicted charm-production fractions as a function of the neutrino energy. The continuous line shows the central value of the f_h as measured by E531, while the dashed lines the upper and lower bounds at 68% C.L.

Table 8
Charmed hadron semi-muonic branching ratios and V_{cd} measured by various experiments at different neutrino energies. The direct measurement performed by CHORUS is also shown

Collaboration	E_ν (GeV)	$B_\mu \vert V_{cd}\vert^2$	B_μ
CDHS [21]	20.0	$(0.41 \pm 0.07) \times 10^{-2}$	0.083 ± 0.014
CHARM II [22]	23.6	$(0.442 \pm 0.049) \times 10^{-2}$	0.090 ± 0.010
NOMAD [23]	23.6	$(0.48 \pm 0.17) \times 10^{-2}$	0.097 ± 0.034
CHORUS [13]	27		0.093 ± 0.013
CCFR (LO) [24]	140	$(0.509 \pm 0.036) \times 10^{-2}$	0.103 ± 0.007
CCFR (NLO) [25]	140	$(0.534 \pm 0.060) \times 10^{-2}$	0.108 ± 0.012
PDG [4] (From unitarity at 90%)	$V_{cd} = 0.219$–0.225	$\langle V_{cd}\rangle = 0.222 \pm 0.003$	

a very important quantity, being the input variable needed to extract from the dimuon data the element of the CKM matrix V_{cd}.

Recently, a direct measurement of $\overline{B}_\mu$ has been performed by the CHORUS Collaboration by using a statistics of about 1000 charm events reconstructed in the nuclear emulsions. Out of these, $(88 \pm 10 \pm 8)$ dimuon events have been reconstructed, which correspond to [13]

$$\overline{B}_\mu = (9.3 \pm 1.3)\%.$$

This measurement has to be compared with our prediction obtained by convoluting the charm-production fractions with the CHORUS neutrino flux

$$\overline{B}_\mu = (8.8 \pm 1.0)\%.$$

In Table 8 we derived, by using the V_{cd} value obtained by imposing the unitarity constraint to the CKM matrix and the measurements of $B_\mu |V_{cd}|^2$ from various experiments, B_μ. Given the fact that the different experiments exploit different neutrino energy spectra, we can probe the sensitivity of B_μ to the neutrino energy. As expected, the higher the neutrino beam energy the larger the value of B_μ.

4. Conclusions

We have presented a method to extract the charmed fractions in neutrino induced events. The method relies on the fact that, apart from processes peculiar to neutrinos such as quasi-elastic and diffractive charm-production, the charm-production and fragmentation mechanism is believed to be process-independent. We have verified this natural assumption going through a complete review of the available data from different experiments. Moreover, the D^+ over D^0 ratio is constant over the large energy range spanned by the collider and fixed target experiments reviewed in this Letter. By using recent data from neutrino experiments, we have assessed the consistency of this ratio with the one predicted by other experiments. On the other side, the energy-independent behavior of the ratio itself is clear from the review of the experiments.

Threshold effects for the D_s production are seen and accounted for. By introducing the diffractive charm-production and using the unity constraint, we have predicted the charm fragmentation as a function of the neutrino energy in the range useful to present neutrino experiments. In particular, a prediction for the CHORUS experiment has been made. The determination of the fragmentation function also allows the prediction of the semi-muonic branching ratio of charmed hadrons. The prediction given is in good agreement with a recent measurement made by the CHORUS experiment.

References

[1] Fermilab E531 Collaboration, N. Ushida, et al., Phys. Lett. B 206 (1988) 380.
[2] T. Bolton, hep-ex/9708014.
[3] NA14/2 Collaboration, M.P. Alvarez, et al., Z. Phys. C 60 (1993) 53.
[4] Particle Data Group Collaboration, D.E. Groom, et al., Eur. Phys. J. C 15 (2000) 1.
[5] BES Collaboration, J.Z. Bai, et al., Phys. Rev. D 62 (2000) 012002, hep-ex/9910016.
[6] M.W. Coles, et al., Phys. Rev. D 26 (1982) 2190.
[7] CLEO Collaboration, D. Bortoletto, et al., Phys. Rev. D 37 (1988) 1719;
D. Bortoletto, et al., Phys. Rev. D 39 (1989) 1471, Erratum.
[8] ARGUS Collaboration, H. Albrecht, et al., Z. Phys. C 52 (1991) 353.
[9] L. Gladilin, hep-ex/9912064.
[10] BEATRICE Collaboration, M. Adamovich, et al., Nucl. Phys. B 495 (1997) 3.
[11] BEATRICE Collaboration, M. Adinolfi, et al., Nucl. Phys. B 547 (1999) 3.
[12] CHORUS Collaboration, A. Kayis-Topaksu, et al., Phys. Lett. B 527 (2002) 173.
[13] CHORUS Collaboration, A. Kayis-Topaksu et al., Phys. Lett. B, in press, preprint CERN-EP-2002-075.
[14] C.G. Wohl, Particle Data Group note, unpublished.
[15] Big Bubble Chamber Neutrino Collaboration, A.E. Asratian, et al., Z. Phys. C 68 (1995) 43.
[16] NOMAD Collaboration, P. Astier, et al., Phys. Lett. B 526 (2002) 278.
[17] S. Chun, C. Buchanan, Phys. Rep. 292 (1998) 239.
[18] G. De Lellis, A. Marotta, P. Migliozzi, J. Phys. G 28 (2002) 713;
G. De Lellis, A. Marotta, P. Migliozzi, J. Phys. G 28 (2002) 1515, hep-ph/0201050, Erratum.
[19] M.S. Chen, F.S. Henyey, G.L. Kane, Nucl. Phys. B 118 (1977) 345.
[20] G. De Lellis, P. Migliozzi, P. Zucchelli, Phys. Lett. B 507 (2001) 7, hep-ph/0104066.
[21] H. Abramowicz, et al., Z. Phys. C 15 (1982) 19.
[22] CHARM II Collaboration, P. Vilain, et al., Eur. Phys. J. C 11 (1999) 19.
[23] NOMAD Collaboration, P. Astier, et al., Phys. Lett. B 486 (2000) 35.
[24] S.A. Rabinowitz, et al., Phys. Rev. Lett. 70 (1993) 134.
[25] CCFR Collaboration, A.O. Bazarko, et al., Z. Phys. C 65 (1995) 189, hep-ex/9406007.